Summary of the 3rd International Workshop on a Far Detector in Korea for the J-PARC Beam

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1. Introduction

The 3rd International Workshop on a Far Detector in Korea for the J-PARC Neutrino Beam*† was held at the Hongo Campus of Tokyo University, Tokyo, Japan on Sep. 30th and October 1, 2007. Forty seven physicists from Japan and Korea, as well as Europe and USA, participated in the workshop and discussed the physics opportunities offered by the J-PARC conventional neutrino beam detected by a new large underground neutrino detector in Korea. In this paper, we highlight some of the most relevant findings of the workshop.

The present neutrino physics program in Korea, focused at a reactor neutrino experiment RENO, and the state of the J-PARC neutrino beam, presently under construction at Tokai (Japan) for the T2K experiment, were reviewed at the workshop. Future long baseline neutrino experiments have the task to complete the present knowledge on the mixing parameters, possibly including the CP violating phase δ. The measurements in RENO and T2K could indicate a non-vanishing θ_{13} angle, thereby ascertaining the 3×3 nature of the lepton flavor mixing matrix. They may conclude that the simultaneous determination of the neutrino mass hierarchy and the CP violating phase is possible at a next generation long baseline experiment coupled to a high intensity conventional neutrino beam.

The idea of a long baseline neutrino experiment from Japan to Korea as a future extension of the J-PARC neutrino beam program beyond T2K was debated, following the discussions held at the 1st and 2nd workshops of this series. One of the specific purpose of this 3rd workshop was to further uncover the physics potential of the detector in Korea, to discuss the various issues related to detector technologies, to address in more details systematic errors affecting the measurements, to investigate possible synergies between RENO and the potential long-baseline program, and to globally consider all physics opportunities offered by such an experiment.

Several options for the construction of a new large underground neutrino detector in Korea were addressed. Many different parameters such as location, depth, off-axis angle, detector mass, or detector technology, etc. can in principle be optimized to best detect the J-PARC neutrino beam. In particular, the choice of the off-axis angle allows to optimize the neutrino beam shape, the smaller off-axis angles yielding a broader and more energetic neutrino spectrum, while the larger angles corresponding to narrow band beams at given neutrino energies. The discussion primarily centered on two categories of detector site locations; one is

*http://www-rccn.icrr.u-tokyo.ac.jp/workshop/T2KK07/

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the site nearest to the on-axis beam trajectory which would receive a wide-band beam extending to a few GeV, and the other at 2.5^o off-axis (OA) for receiving a sub-GeV neutrino beam with the identical energy spectrum as in Kamioka.

Water Cherenkov and liquid Argon detectors were discussed as candidates for detector technologies. The "baseline setup" assumed a very large deep underground Water Cherenkov imaging detector of about 300 kton fiducial volume located in Korea at the same off-axis angle as Super-Kamiokande, complementing another new similarly large detector at a new site in Kamioka. Similar configurations but with different off-axis angles were considered, paying attention to background events, in particular for smaller OA angles. A large 100 kton liquid Argon Time Projection Chamber at an OA1.0 in Korea was also considered, offering similar and complementary physics performance.

Several possible sites for the detector were mentioned, many of these with significant overburden, this latter condition being most relevant for the study of atmospheric and supernovae neutrinos, and for the search of proton decay. The Korean geological conditions are favorable, however more information for deep geological conditions are missing at this stage. A more detailed geotechnical characterization will be needed to reduce potential risks for construction.

Overall, it was recognized through the workshop discussions that a long baseline experiment from Tokai to Korea could give important information with which to understand the properties of neutrinos. In particular, the neutrinos with long flight path in matter could be crucial to determine the neutrino mass hierarchy, and lifting ambiguities in the measurement of the leptonic CP violation phase. Non-accelerator based neutrino physics and the search for proton decay in a large underground detector would also address fundamental questions of particle and astroparticle physics.

The results from the RENO and T2K experiments and more detailed studies are required to fully optimize the advantages of a Korean detector. Development of detector technologies must continue and more detailed investigations of the site are mandatory. It was decided to hold a forth workshop to further explore and update the opportunities of this very exciting physics program.

2. The RENO reactor neutrino experiment

An experiment, RENO (*R*eactor *E*xperiment for *N*eutrino *O*scillation) [1], is under construction to measure the smallest and unknown neutrino mixing angle (θ_{13}) using anti-neutrinos emitted from the Yonggwang nuclear power plant in Korea with world-second largest thermal power output of 16.4 GW. The experimental setup consists of two identical 15-ton Gadolinium loaded liquid scintillator detectors located near and far from the reactor array to measure the deviations from the inverse square distance law. The near and far detectors are to be placed roughly 290 m and 1.4 km from the center of the reactor array, respectively. The experiment is planned to start data-taking in early 2010. An expected number of observed anti-neutrino is roughly 5 000 per day and roughly 100 per day in the near detector and far detector, respectively. An estimated systematic uncertainty associated with the measurement is less than 0.5%. Based on three years of data, it would be sensitive to measure the neutrino mixing angle in the range of $\sin^2(2\theta_{13}) > 0.02$. This sensitivity is more than five times better than the current limit obtained by CHOOZ [2].

3. The T2K accelerator neutrino experiment

The construction of J-PARC [3], the Japan Proton Accelerator Research Complex, a joint facility of High Energy Accelerator Research Organization (KEK) and Japan Atomic Energy Agency (JAEA) was in part inspired by the requirements of the T2K experiment [4], the next generation long baseline experiment between J-PARC and Super-Kamiokande. The primary motivation of T2K is to improve

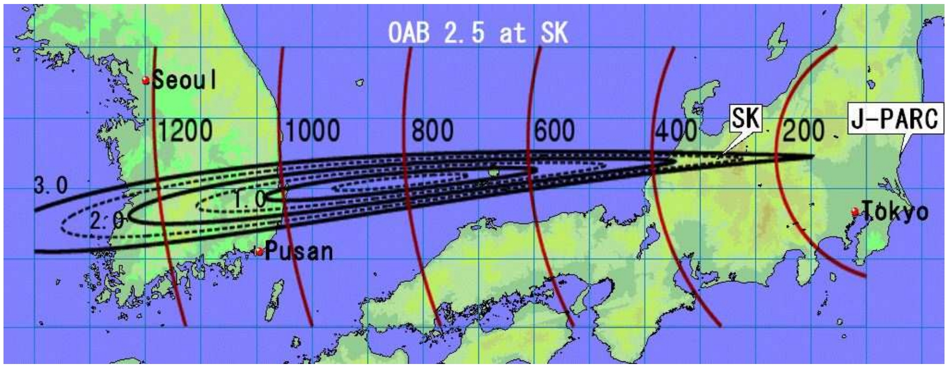

Fig. 1 Neutrino beam from J-PARC reappears in the Korean peninsula [7]. The solid lines with the numbers n imply locations at which neutrino beam of n degree off axis intersect with the earth surface (sea level). The red lines with the numbers denote the equi-distance curves from J-PARC in units of km.

the sensitivity to the $\nu_\mu \to \nu_e$ conversion phenomenon in the atmospheric regime by about an order of magnitude compared to CHOOZ [2].

The J-PARC accelerator complex which includes the 180 MeV LINAC, the 3 GeV Rapid Cycling Synchrotron (RCS) and the 30-50 GeV Main Ring Synchrotron (MR) is planned to be commissioned in 2008. The J-PARC neutrino beam facility, under construction for the T2K experiment, is foreseen to begin operation in 2009 [5]. The final goal for the T2K experiment is to accumulate an integrated proton power on target of 0.75 MW$\times 5 \times 10^7$ seconds. Within a few years of run, critical information, which will guide the future direction of the neutrino physics, will be obtained based on the data corresponding to about $1 \div 2$ MW $\times\ 10^7$ seconds integrated proton power on target (roughly corresponding to a 3σ discovery at $\sin^2 2\theta_{13} > 0.05$ and 0.03, respectively) [6].

4. Concept of the J-PARC-Korea long baseline neutrino program

The J-PARC-Korea long baseline neutrino experiment is a natural continuation of the physics addressed by RENO and T2K. Let us start by describing the general concept of the J-PARC-Korea setup. We intend to make generic points which are valid without recourse to any specific setup.

- The final goal for the T2K experiment is to reach an integrated intensity of 5×10^{21} pots, or equivalently a neutrino beam power of ~ 0.75 MW during 5 years. There is a plan to further upgrade the accelerator complex to potentially provide an increased beam power of 1.66 MW to the neutrino target [6]. This upgrade should in principle not require major modifications in the beamline infrastructure which has been designed up to 2 MW. At this workshop, we assume an upgraded 4MW J-PARC beam created from 40 GeV protons, running 1.12×10^7 seconds per year was assumed. This is equivalent to 28×10^{21} POT per year.

- The neutrino beam from J-PARC, according to the current design, automatically reappears in the Korean peninsula. See Fig. 1 which is taken from [7]. Therefore, it is a cost effective way to build a new experiment by having a far

detector at an appropriate site in Korea, allowing in principle simultaneous measurements at Kamioka (L=295 km) and Korea (L≈ 1000 km).

- To determine the CP violating phase and the neutrino mass hierarchy, a powerful tool is to measure electron neutrino appearance at both the first and second oscillation maximum. Two different approaches are possible in order to make this measurement:

  (1) one option is to have two detectors in the same beam (i.e. at the same off-axis angle), each of them positioned mainly at one oscillation maximum, either the first or second [8]. In this way many of the systematic errors can cancel or can be correlated with each other. The best situation could be achieved if both detectors were built in an identical way. This was defined as the "baseline setup";

  (2) another approach, is to use a wide-band energy beam, and measure electron neutrino appearance from both the first and second maxima with the same detector [9, 10], by realizing that if one can observe multiple oscillation maxima of neutrino oscillation, $\Delta m^2_{31} L/2E = (2n+1)\pi$ (n=0, 1, 2, ...), such measurement will have sensitivities to the mass hierarchy as well as CP violation phase in a single experiment.

- By placing a detector somewhere in Korea at a baseline of about 1000 km, the experiment becomes sensitive to the matter effects in neutrino oscillation. It will give the experiment the ability of resolving the neutrino mass hierarchy, otherwise impossible at L=295 km.

5. Determination of CP-violation phase and neutrino mass hierarchy

The neutrino beam spectrum in Korea will depend on the off-axis angle and on the exact geographical location chosen, because of the non-cylindrical shape of the decay tunnel in the neutrino beam line [11]. When the upper side of the beam at 2° to 3° off-axis angle is observed at Super-Kamiokande, the lower side of the same beam at 0.5° to 3.0° off-axis angle can be observed in Korea. As indicated in Fig. 1 the J-PARC neutrino beam, to which the Kamioka detector is placed at 2.5 degrees off-axis, reappears in Korean peninsula as a beam with off-axis angle larger than 1 degree. Then, depending upon the off-axis angle chosen, a wide range of neutrino energy spectra becomes available [11], as exhibited in Fig. 2.

In the first published article[8], the off-axis angle of the Korean detector was assumed to be 2.5°. The expected performance of this setup was recalled at this workshop [12].

It was argued that using a higher energy beam is better for the mass hierarchy determination due to the larger matter effect [13, 14]. However, experimentally, one expects higher background rate in the sub-GeV energy range for the higher energy beam due to the larger amount of neutral current contamination. Therefore one has to estimate the expected background carefully in order to compare the sensitivities of the low and high energy beam options.

The possibility of using wide-band beam for the detector in Korea with the background estimation was discussed [15, 16]. In Fig. 3 the understanding of the signal and background events in a water Cherenkov detector for various off-axis angle is presented [15]. One can recognize that there is an accumulation of background events at low energies which comes from high energy tail of the neutrino energy spectrum. This feature makes it highly nontrivial to reject background in an unambiguous way in water Cherenkov detectors.

With the current understanding of the background one can examine if the near on-axis detector in Korea improves the sensitivities to the mass hierarchy and CP violation. In Fig. 4, off-axis angle dependence of the sensitivity to the mass

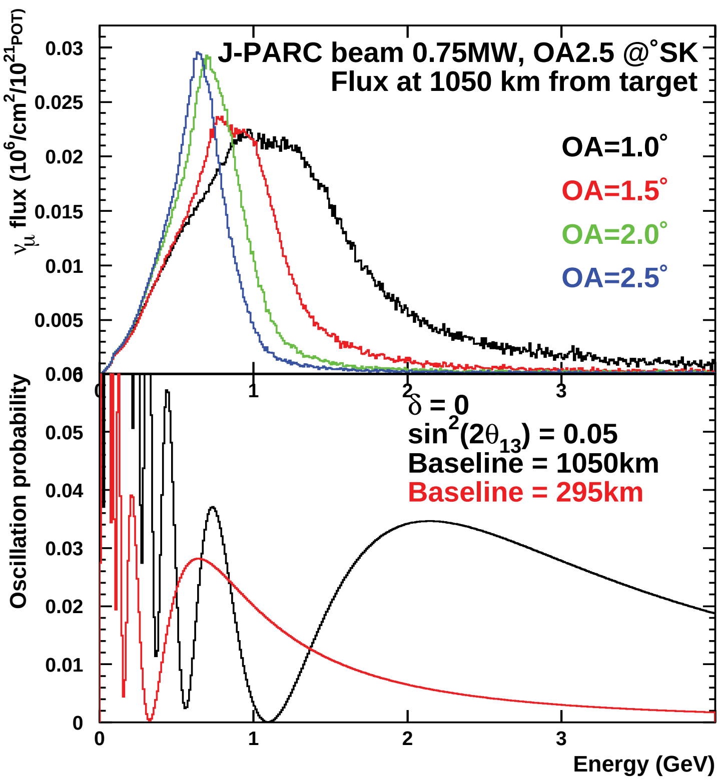

Fig. 2 Neutrino flux as a function of energy for several off-axis angle, and a 0.75MW beam at 1050km from the target. For comparison, the $\nu_\mu \to \nu_e$ probability, for the two baseline considered in T2KK (295km and 1050km), for $\Delta m^2_{(21,31)} = 7.3 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ and the other mixing angles at $\sin^2 2\theta_{(12,23)} = 0.86, 1.0$. We assumed the earth density to be constant and to be equal to 2.8 g/cm^3

hierarchy and CP violation are shown [17]. The sensitivity to the mass hierarchy resolution improves with the decreasing off-axis angles (namely with the increasing beam energy) while the CP violation results remain essentially intact. This is the most attractive feature of the near-on-axis option of the Korean detector. The improved sensitivity to the mass hierarchy is indeed expected. The near on-axis Korean detector can cover the neutrino energy spectrum including the first and the second oscillation maxima with much higher event rate in the former region, i.e., at higher energies. The matter effect is stronger in this region and hence the higher resolving power for the mass hierarchy.

However, a cautionary remark for the interpretation of the above results has been expressed [12]. The statistical procedure used to produce Fig. 4 is identical with that used in the analysis of two identical detector case [8], which means that most of the systematic errors are assumed to be completely correlated between the two detectors. Therefore, a careful reanalysis is called for including more realistic systematic errors [18, 19, 20]. It was also pointed out that a careful treatment of the Earth matter profile is mandatory [21]. Nonetheless, improvement of potential

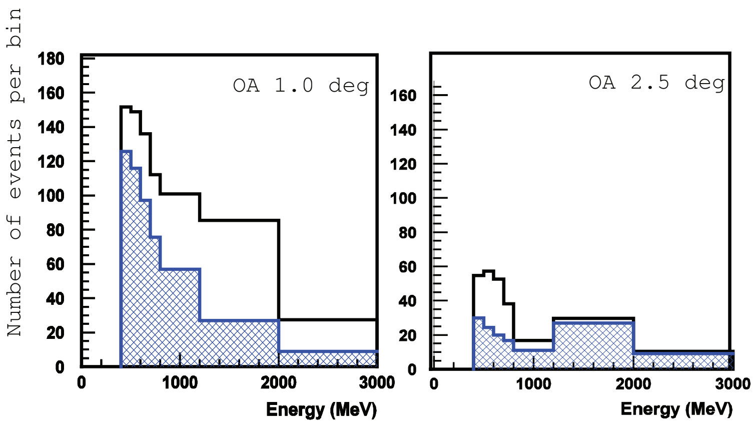

Fig. 3 Expected background (hatched regions) for the electron appearance search for the Korean detectors with off-axis angles 1.0(left) and 2.5(right) degrees. Also shown are the expected signal (solid histograms) over the background for $\sin^2 2\theta_{13} = 0.1$ and $\delta = \pi/2$.

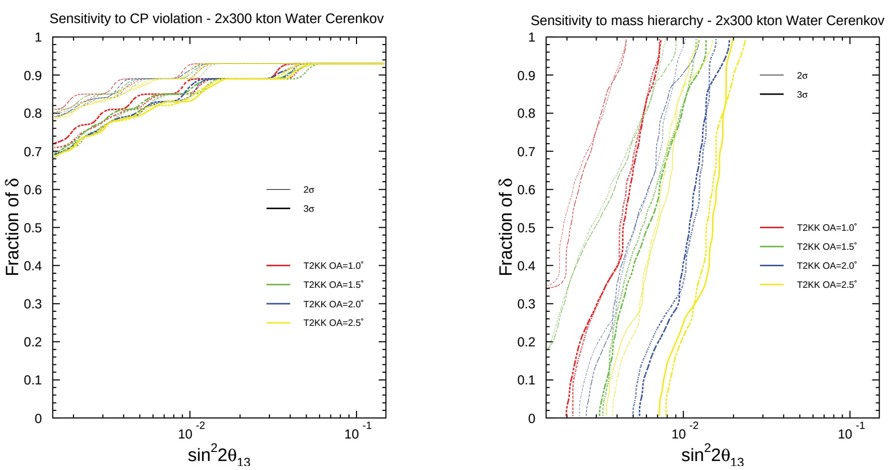

Fig. 4 Sensitivities [17] to CP violation (left) and mass hierarchy (right) for different values of the off-axis angle assuming 2×300 kton fiducial volume Water Cerenkov detectors. (Other parameters: $\Delta m^2_{(21,31)} = 7.3 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ and the other mixing angles: $\sin^2 2\theta_{(12,23)} = 0.86, 1.0$. We assumed the earth density to be constant and to be equal to 2.8 g/cm^3)

for the mass hierarchy determination is likely to survive in a proper treatment because of the physics arguments presented above.

Another option one could take for the high energy beam is to use a much advanced detector technology to consider all events around the GeV region and above (while the WC technology is essentially limited to quasi-elastic events) and simultaneously reduce the neutral current background as much as possible. One such example could be a very large Liquid Argon Time Projection Chamber [22]. The imaging properties and the good energy resolution of the LAr TPC would allow studying the broader band beam with the OA1 off-axis angle, covering more features of the oscillation probability (e.g. first maxima, first minima, second maxima, etc.) [16]. In such detectors, the rejection of the neutral current background events will be achieved much more efficiently, reducing the background events in the higher energy beam [22, 16]. Fig. 5 shows the expected sensitivity of the liquid argon detector located at the 1.0 degree off-axis in Korea [23]. It is clear that the sensitivity of the experiment will be very high even for very small $\sin^2 2\theta_{13}$ values.

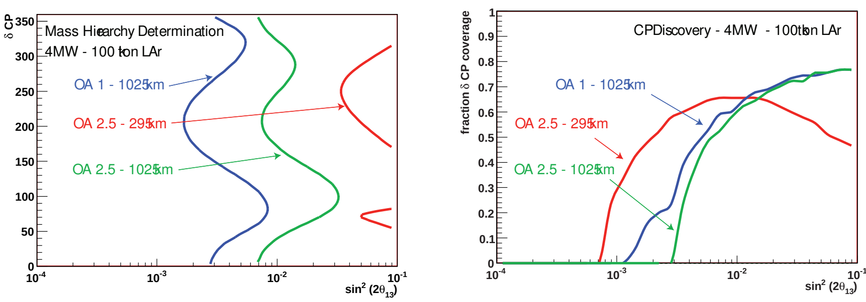

Fig. 5 The expected sensitivities [23] to the mass hierarchy (left) and CP violation (right) are presented in the form of the CP fraction assuming a single 100 kton LAr TPC far detector in Korea. The sensitivity to mass hierarchy is based on the neutrino beam only. The dotted and solid lines are for sensitivities at 90% and 3σ CL, respectively.

In addition to the physics topics summarized so far, various other possibilities of physics measurements to be carried out with the Korean detector and the neutrino beam were discussed at the workshop [24, 25, 26].

One such example was the sensitivity to the octant of θ_{23} based on data from RENO and a next generation underground long-baseline neutrino experiment in Korea. It was concluded that the combined results should show the sensitivity in the octant of θ_{23}, if $\sin^2 2\theta_{13}$ is large (> 0.05) [24].

Another interesting study was on the non-standard neutrino interactions and properties. It is interesting to note that the two detectors setup is powerful to constrain several non-standard nature of neutrinos [25].

6. Detector technologies

The two detector technologies considered are a massive deep underground Water Cherenkov imaging (WC) detector with a fiducial mass of 300-500 kton, and a fully active finely grained liquid Argon time-projection-chamber (LAr TPC) with a mass of ~ 100 kton.

6.1. Large Water Cherenkov Imaging detector

Two generations of large water Cherenkov detectors at Kamioka (Kamiokande[27] and Super-Kamiokande[28]) have been very successful in research of neutrino physics with astrophysical sources. In addition, the first long baseline neutrino oscillation experiment with accelerator-produced neutrinos, K2K [29], has been conducted with Super-Kamiokande as far detector. Super-Kamiokande is composed of a tank of 50 kton of water (22.5 kton fiducial) which is surrounded by 11146 20-inch phototubes immersed in the water. About 170 γ/cm are produced by relativistic particles in water in the visible wavelength $350 < \lambda < 500$ nm. With 40% PMT coverage and a quantum efficiency of 20%, this yields ≈ 14 photoelectrons per cm or ≈ 7 p.e. per MeV deposited.

There are good reasons to consider a third generation water Cherenkov detector with an order of magnitude larger mass than Super-Kamiokande: a megaton Water Cherenkov detector will have a broad physics programme, including both non-accelerator (proton decay, supernovae, ...) and accelerator physics.

Hyper-Kamiokande [30] has been proposed with about 1 Mton, or about 20 times as large as Super-Kamiokande, based on a trade-off between physics reach and construction cost. Further scaling is limited by light propagation in water (scattering, absorption). Although this order of magnitude extrapolation in mass is often considered as straight-forward, a number of R&D efforts including the site selection are needed before designing the real detector. An important item for Hyper-Kamiokande is developments of new photo-detectors: with the same photo-sensitive coverage as that of Super-Kamiokande, the total number of PMTs needed for Hyper-Kamiokande will be $\simeq 200000$. Possibilities to have devices with higher quantum efficiency, better performance, and cheaper cost are being pursued.

6.2. Liquid Argon Time Projection Chamber

Among the many ideas developed around the use of liquid noble gases, the Liquid Argon Time Projection Chamber (LAr TPC) (See Ref. [31] and references therein) certainly represented one of the most challenging and appealing designs. The LAr TPC is a powerful detector for uniform and high accuracy imaging of massive active volumes. It is based on the fact that in highly pure Argon, ionization tracks can be drifted over distances of the order of meters. Imaging is provided by position-segmented electrodes at the end of the drift path, continuously recording the signals induced. T_0 is provided by the prompt scintillation light.

One possible design for a detector with mass order of 100 kton, called GLACIER concept [32], was assumed at this workshop. The pros and cons of the LAr TPC, in particular in comparison to the Water Cherenkov Imaging technique, can be summarized as follows:

The liquid Argon TPC imaging should offer optimal conditions to reconstruct the electron appearance signal in the energy region of interest in the GeV range, while considerably suppressing the NC background consisting of misidentified π^0's. The signal efficiency is expected to be higher to that of the WC detector, hence, the LAr TPC detector could be smaller: the 100 kton detector considered here is approximately twice the size of the Super-Kamiokande detector. In addition, a LAr TPC should allow operation at shallow depth. The constraints on the excavation and the related siting issues of the detector should hence be reduced compared to WC.

The community has less experience with the LAr TPC technology than the WC; the largest detector ever operated, the ICARUS T300, has a modular design which is not easily extrapolated to the relevant masses. Significant R&D and

improvements in the design are therefore required in order to reach a scalable design which could offer a path for a 100 kton mass facility in a cost effective way.

The procurement and underground handling of large amounts of liquid Argon is more difficult than that for water, however, safe, surface or near-surface, storage of very large amounts of cryogen (with volumes larger than the ones considered here) has been achieved by the petrochemical industry; liquid Argon is a natural by-product of air liquefaction which has large industrial and commercial applications and can be in principle produced nearby any chosen location.

7. Preliminary site study

Throughout Korea, mountains are not high, rarely exceeding 1,200 meters, but they are found almost everywhere. The terrain is rugged and steep, and only near the west and southwest coasts are extensive flat alluvial or diluvial plains and more subdued rolling hilly lands. Several sites have been considered in a preliminary way: the preferable locations are either a mountain, a mine, or a tunnel. The use of abandoned/closed mines might have some advantages, however, none seemed to satisfy the necessary conditions. Large underground caverns in Korea in the range of 100000 m^3 and depths ranging from 150 m down to 350 m exist and are used for oil, LPG, food and water storage. The general procedure for underground civil engineering construction foresees (a) preliminary data collection (preliminary assessment, preliminary geotechnical characterization), (b) a feasibility study (engineering classification of rock mass, feasibility assessment of tunneling problems & alternatives), (c) a detailed site characterization (d) stability analyses and (e) final design and construction. These have not yet been fully addressed. In conclusion, mountains or shallow depth caverns seem to be most adequate solutions for siting the detector. The Korean geological conditions are favorable, however more information for deep geological conditions are missing at this stage. A more detailed geotechnical characterization will be needed to reduce potential risks for construction [33].

Concerning the Kamioka site, the Mozumi Mine, which is the current Super-Kamiokande site, cannot accomodate Hyper-Kamiokande. A new site in Tochibora at a depth of 1400-1900 m.w.e. was found, which is located about 8 km south of the Mozumi Mine. This location allows for a solution to provide the T2K neutrino beam with the same spectral properties to both Super-Kamiokande and Hyper-Kamiokande [34].

8. Conclusion

All participants of the workshop agreed on the high physics potential of the Korean detector with the J-PARC beam. It was recognized that the results from the RENO and T2K experiments and more detailed studies are required to fully optimize the advantages of a detector in this location. It was decided to hold a forth workshop in Korea to further explore the opportunities of this very exciting physics program.

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